OPIC
OFFICE DE LA PROPRIÉTÉ
INTELLECTUELLE DU CANADA

CIPO
CANADIAN INTELLECTUAL
PROPERTY OFFICE

Ottawa Hull K1A 0C9

(21) (A1) 2,107,388
(22) 1993/11/09
(43) 1995/05/10

(51) INTL.CL. 5 H04N-005/30

(19) (CA) APPLICATION FOR CANADIAN PATENT (12)

(54) Super Decoupled Loadflow Methods

(72) Patel, Sureshchandra B. - India ;

(71) Same as inventor

(57) 1 Claim

5,102,5/41

Notice: This application is as filed and may therefore contain an incomplete specification.

2107388

SUPER DECOUPLED LOADFLOW METODS

ABSTRACT

The complete patent specification involves the invention of six super decoupled loadflow methods. The Fast Super Decoupled Loadflow (FSDL) method and two variants Transformed Fast Decoupled Loadflow (TFDLXB and TFDLBX) methods are known ones and included are their novel versions (NFSDL, NTFDLXB, NTFDLBX). These are the best versions of many simple variants with almost similar performance. These methods specifically involved the use of the following invented technics in the prior art method.

1. Gain matrices of all the six methods are different and they can be determined as described in the specification. Obviously the gain matrices of Pθ-subproblem can be defined unsymmetrical.

2. In all the six methods, rotation angles are restricted to the maximum value of -36 degrees from nonlinearity considerations.

3. Slack-start for any decoupled loadflow method for efficiency

4. Modification of real power mismatches at PV-nodes according to relations (12) and (15) of the specifications for the methods FSDL, TFDLXB, TFDLBX.

5. Computation of angle correction and updating for PV-nodes along with the voltage magnitude corrections at PQ-nodes for NFSDL, NTFDLXB and NTFDLBX methods. In the back-substitution part of the solution of this subproblem involving angle

corrections at PV-nodes and voltage magnitude corrections at PQ-nodes, skip factor elements corresponding to rows and columns of PV-nodes in the calculation of voltage magnitude corrections.

The specification deals only with unadjusted super decoupled loadflow solution methods and does not describe any applications. However the computer algorithms can be appropriately modified for adjustments and/or applications such as state estimation, contingency analysis etc.

Also described and claimed is the invention of two compact storage schemes for gain matrices ofthe FSDL method and two efficient procedures for node type switching implementations in the FSDL method.

Dated this 7 th day of November 1993

Signature of the inventor - S.B.Patel

2107388

THE CANADIAN PATENT ACT

THE COMPLETE SPECIFICATION

SUPER DECOUPLED LOADFLOW METHODS

Sureshchandra Bhagubhai Patel, Indian National,
Resident of village : Dhatva,
Taluka : Kamrej
District : Surat
Gujarat, India.
Pin code : 394 180

Sureshchandra Bhagubhai Patel, In service of
Electrical Engineering Department
BVM Engineering College
Vallabh Vidyanagar
Gujarat, INDIA
Pin code : 388 120

The following specification particularly describes and ascertains the nature of this invention and the manner in which it is to be performed.

This invention relates to the super decoupled methods of steady-state loadflow analysis of power system, and computer algorithms for carrying out these methods.

A computer algorithm processes raw information to yield useful information. A chemical process processes raw material to yield useful material. Useful information is well recognized as technological product in the modern age of information technology. Therefore, the computer algorithm like chemical process yields useful product and it is the useful art.

INTRODUCTION

Loadflow in power system studies is the most basic frequently performed steady state analysis of an electrical power network. The loadflows are performed in system planning, operational planning, and operation control. Of various methods proposed over the past four decades, Stott's Fast Decoupled Loadflow (FDL) [1] has gained wide acceptance both for off- and on- line applications. However, it is known to suffer poor convergence for systems having high R/X ratio branches (discussions in [1] & [2]).

Dy Liacco and Ramarao(discussion of [2]) as well as Deckmann et. al. [3] have developed circuit transformation schemes to avoid such difficulties. The two schemes however do not provide consistent improvement in convergence[4]. Also they are not general and are suitable where the system has a small number of troublesome R/X ratio branches.

A recently introduced super decoupled approach [5,6,7] is more general and reliable. Rotation operators applied to the complex node injections and the corresponding admittance values

that relate the above to the system state variables, transform the network equations such that branch admittances appear to be almost entirely reactive. Thus, better decoupling is realized. However, the super decoupled algorithms are not efficient and are not very convenient in contingency analysis. A recent modification to the FDL method for networks with high R/X ratio branches [4] is in fact variation of the super decoupled approach with a weakness that it takes higher number of iterations for normal cases.

General-purpose version of the Fast Decoupled Loadflow (GFDL) method[8] proposes simple modifications to the classical FDL method. The convergence is much improved in the presence of large R/X ratio lines. The two versions of FDL method are put in a better theoretical framework by Monticelli et. al.[9]. The GFDL method is nothing but an experimental investigation of the original observation made about the behaviour of the FDL method by this inventor as back as 1985 in an unaccepted research paper communicated to IEEE(New York).

The critically coupled loadflow methods are based on the use of the overlap update rule [10]. The disadvantage of the methods is that they involve the solution of a larger number of equations at each iteration. Moreover the tests conducted for the paper[10] avoided the increase of R/X ratio of branches connected to the PV-nodes. Therefore, conclusions of the paper are not based on exhautive testing. Test show that the invented six versions are the best loadflow methods. However, simply modified versions including hybrids of the six invented methods can also have closely similar performance for any given system.

The latest Novel Decoupled Loadflow Method[11] can simply be derived from published[12] and lately claimed invetion of this patent specification. In fact the idea involved in the method of [11] was revealed by this inventor in extensive communication for about four years with Institution of Electrical Engineers of England. Also the idea was investigated along with the modification of the real power mismatches at PV-nodes and only the best method was reported in reference [12]. Moreover the unsymmetrical gain matrix definition for the Pθsubproblem is obvious from the definition of the factor (K) used to modify real power mismatches of the PV-nodes[12]. However the method of [11] is not reliable for systems having PV-nodes and it has no flexibility of tuning rotation angle as was originally known to this inventor. Possibly this may be the reason that the author of [11] did not comapre his method with the Fast Super Decoupled Loadflow[12] and Transformation based Fast Decoupled Loadflow[13] methods.

Keywords : Power systems, Loadflow, Matrices, solution of simultaneous equations.

The invention will now be described, wherein the following symbols are used :

$\bar{Y}_{pq} = G_{pq} + jB_{pq}$: (p-q)-th element of nodal admittance matrix formed excluding shunts

$\bar{y}_p = g_p + jb_p$: total shunt admittance at node p

$\bar{V}_p = e_p + jf_p = V_p \angle\theta_p$: complex voltage at node p

$\Delta\theta_p$, ΔV_p : voltage angle, magnitude corrections

Δe_p, Δf_p : real, imeginary component corrections of voltage

$P_p + jQ_p$: net nodal injected power calculated

$\Delta P_p + j\,\Delta Q_p$: nodal power residue (mismatch)

$RP_p + jRQ_p$: modified nodal power residue

m : number of PQ-nodes

k : number of PV-nodes

n=m+k+1 : total number of system nodes

q>p : q is the node adjacent to node p excluding the case q = p

[ ] : indicates enclosed variables to be vector or matrix

SUPER DECOUPLED LOADFLOW (SDL) METHOD (The prior art)

There are two versions of the Super Decoupled Loadflow method. These are based on the XB- and BX- versions of the Fast Decoupled Loadflow (FDL) method. The one based on the XB-version was developed in 1985 [7] and the other based on the BX-version is obvious from the BX-version of the FDL method developed in 1989 [8]. These methods involve the iterative solution of system of equations (1) and (2). Unlike FDL model the gain matrices in its transformed version are unsymmetrical because mostly different rotations are required to be applied at the terminal nodes of a branch. Symmetrical gain matrices can be obtained by the Haley and Ayres technique [7] of applying average of the rotations at the terminal nodes of a branch to the branch admittance (appendix).

SDL based on the XB-version of the FDL (SDLXB)

The SDLXB-version is described by the following equations (1) to (10).

$$[RP] = [Y'] [\Delta\theta] \tag{1}$$

$$[RQ] = [Y''] [\Delta V] \tag{2}$$

Wherein each element of [RP] and [RQ] at PQ-nodes are given by (3) and (4) respectively. Whereas an element of [RP] at PV-nodes is given by (5).

$$RP_p = (\Delta P_p \cos\phi_p + \Delta Q_p \sin\phi_p)/V_p \tag{3}$$

$$RQ_p = (-\Delta P_p \sin\phi_p + \Delta Q_p \cos\phi_p)/V_p \tag{4}$$

$$RP_p = \Delta P_p / V_p \tag{5}$$

Trigonometric functions in (3) and (4) and elements of [Y'] and [Y"] are given by (6), (7) and, (8), (9) and (10).

$$\cos\phi_p = -B_{pp} / \sqrt{G_{pp}^2 + B_{pp}^2} \tag{6}$$

$$\sin\phi_p = -G_{pp} / \sqrt{G_{pp}^2 + B_{pp}^2} \tag{7}$$

$$Y'_{pq} = -1 / \tilde{X}_{pq} \quad \text{and} \quad Y''_{pq} = -\tilde{B}_{pq} \tag{8}$$

$$Y'_{pp} = \sum_{q \neq p} -Y'_{pq} \quad \text{and} \quad Y''_{pq} = -2b'_p + \sum_{q \neq p} -Y''_{pq} \tag{9}$$

$$b'_p = b_p \cos\phi_p \quad \text{or} \quad = b_p \tag{10}$$

Where $\tilde{X}_{pq}$ is the transformed branch reactance defined in appendix by eqation (41) and $\tilde{B}_{pq}$ is the corresponding transformed element of the susceptance matrix.

SDL based on the BX-version of the FDL (SDLBX)

The SDLBX-version differs from the SDLXB-version only in relation (8) as given by relation (11). The SDLBX-version consists of relations (1) to (7), (11), (9) and (10).

$$Y'_{pq} = -\tilde{B}_{pq} \quad \text{and} \quad Y''_{pq} = -1 / \tilde{X}_{pq} \tag{11}$$

INVENTED SUPER DECOUPLED LOADFLOW METHODS

Six invented super decoupled loadflow models are described in this section. Fast Super Decoupled and two versions of the Transformed Fast Decoupled models are Known ones [12,13] and included are their novel versions.

Fast Super Decuopled Loadflow (FSDL)

The FSDL method involves the iterative solution of the system of equations (1) and (2). The model cosists of relations (1) to (4), (6), (7), (12) to (16), (9) and (10).

$$RP_p = \Delta P_p / (K_p V_p) \tag{12}$$

Elements of [Y'] and [Y"] and the multiplier K_p in (12) are given by :

$$\begin{aligned} Y'_{pq} &= -Y_{pq} && \text{for branch r/x ratio} \leq 2.0 \\ &= -(B_{pq} + 0.9(Y_{pq} - B_{pq})) && \text{for branch r/x ratio} > 2.0 \\ &= -\cancel{B_{pq}}\ B_{pq} && \text{for branches connected between two PV-nodes or a PV-node and the slack-node} \end{aligned} \tag{13}$$

$$\begin{aligned} Y''_{pq} &= -Y_{pq} && \text{for branch r/x ratio} \leq 2.0 \\ &= -(B_{pq} + 0.9(Y_{pq} - B_{pq})) && \text{for branch r/x ratio} > 2.0 \end{aligned} \tag{14}$$

$$K_p = \text{Absolute}\ (B_{pp}/Y'_{pp}) \tag{15}$$

$$KKp = \text{Absolute}\ (Y'pp/Y''pp) \tag{16}$$

Branch admittance magnitude in (13) and (14) is of the same algebraic sign as its susceptance. Elements of the two gain matrices differ in that diagonal elements of [Y"] additionally contain the b' values given by equation (10) and in respect of elements corresponding to branches connected between two PV-nodes or a PV-node and the slack-node. The factor 0.9 in the relations (13) and (14) is tuned only for rotation limited to -36 degrees. With different Limiting Rotation Angle(LRA), it needs to be tuned again. In two simple variations of the FSDL method, one is to make $Y''_{pq} = Y'_{pq}$ and the other is to make $Y'_{pq} = Y''_{pq}$.

Transformation based Fast Decoupled Loadflow (TFDL)

The TFDL model is similar to the FSDL model. They differ only in the definition of the gain matrices.

The TFDL(XB-version) (TFDLXB) Loadflow

The TFDLXB-version consists of relations (1) to (4), (12), (15), (6), (7), (17), (18), (19), (9) and (10).

$$Y'pq = \begin{cases} -Bpq & \text{for branches connected between two PV-nodes or a PV-node and the slack-node} \\ -1 / \tilde{X}_{pq} & \text{for all other branches} \end{cases} \tag{17}$$

$$Y''_{pq} = -\tilde{B}_{pq} \tag{18}$$

$$KK_p = \text{Absolute}\ (Y'_{pp}/(\sum_{p \neq q} 1/\tilde{X}_{pq})) \tag{19}$$

The TFDL(BX-version) (TFDLBX) Loadflow

The TFDLBX-version consists of relations (1) to (4), (12), (15), (6), (7), (20), (21), (22), (9) and (10).

$$Y'_{pq} = \begin{cases} -B_{pq} & \text{for branches connected between two PV-nodes or a PV-node and the slack-node} \\ -\tilde{B}_{pq} & \text{for all other branches} \end{cases} \qquad (20)$$

$$Y''_{pq} = -1 / \tilde{X}_{pq} \qquad (21)$$

$$KK_p = \text{Absolute}\ (Y'_{pp} / (\sum_{q \to p} \tilde{B}_{pq})) \qquad (22)$$

Where $\tilde{X}_{pq}$ is the transformed branch reactance defined in appendix by eqation (41) and $\tilde{B}_{pq}$ is the corresponding transformed element of the susceptance matrix.

The factor KK_p is to be multiplied to the real power mismatch at a PV-node switched to PQ-type in node type switching implementation. From general considerations, K_p and KK_p are restricted to the minimum value of 0.75 for FSDL, TFDLXB and TFDLBX methods. However they can be tuned for the best possible convergence for any given system.

In all the SDLXB, SDLBX, FSDL, TFDLXB and TFDLBX models [Y'] and [Y"] are real, sparse, symmetrical and built only from network elements. Since they are constant, they need to be factorized once only at the start of the solution. Equations (1) and (2) are to be solved repeatedly by forward and backward substitutions.

[Y'] and [Y"] are of the same dimensions (m+k)*(m+k) when only a row/column of the slack-node is excluded and both are triangularized using the same ordering regardless of the node-types. For a row/column corresponding to a PV-node excluded in [Y"], use a large diagonal to mask out the effects of the off-diagonal terms. When the node is switched to the PQ-state the row/column is reactivated by removing the large diagonal. This technique is especially useful in the treatment of PV-nodes in the matrix [Y"].

It is invented to make this technique efficient while solving (2) for ΔV by skipping all PV-nodes and factor elements with indices corresponding to PV-nodes. In other words efficiency can be realized by skipping operations on rows/columns corresponding to PV-nodes in the forward-backward solution of (2) for ΔV. This has been implemented and the time saving of about 4% of the total solution time (including input/output) could be realized in 14-14 iterations required to solve 118-node system with the uniform R-scale factor 4 applied. The time saving has been assessed on PC-XT. It should be noted that the same indexing and addressing information can be used for the storage of both the matrices as they are of the same dimensions and sparsity structure.

Novel Fast Super Decoupled Loadflow (NFSDL)

The NFSDL method involves the iterative solution of the following system of equations (23) and (24).

$$[RP] = [Y1]\,[\Delta\theta] \tag{23}$$

$$\begin{bmatrix} RQ(PQ\text{-nodes}) \\ RP(PV\text{-nodes}) \end{bmatrix} = \begin{bmatrix} Y2 \end{bmatrix} \begin{bmatrix} \Delta V(PQ\text{-nodes}) \\ \Delta\theta(PV\text{-nodes}) \end{bmatrix} \tag{24}$$

Wherein each element of [RP] and [RQ] at PQ-nodes are given by (3) and (4) respectively. Whereas an element of [RP] at PV-nodes is given by (5). In (24) PV-nodes are assumed to be grouped and numbered after all PQ-nodes.

Elements of [Y1] and [Y2] are given by :

$$Y'_{pq} = \begin{cases} -Y_{pq} & \text{for branch r/x ratio} \leq 2.0 \\ -(B_{pq} + 0.9(Y_{pq} - B_{pq})) & \text{for branch r/x ratio} > 2.0 \\ -B_{pq} & \text{for branches connected between two PV-nodes or a PV-node and the slack-node} \end{cases} \quad (25)$$

$$Y2_{pq} = \begin{cases} G_{pq} & \text{for branches connected to a PQ-node and a PV-node} \\ -Y1_{pq} & \text{for branches connecting two PQ-nodes} \\ Y1_{pq} & \text{for branches connecting two PV-nodes} \end{cases} \quad (26)$$

$$Y1_{pp} = \sum_{q \neq p} -Y1_{pq} \quad (27)$$

$$Y2_{pp} = \begin{cases} 2b_p - Y1_{pp} & \text{for PQ-nodes} \quad 2b'_p - Y1_{pp} \\ -B_{pp} & \text{for PV-nodes} \end{cases} \quad (28)$$

The NFSDL model consists of relations (23), (24), (3) to (7), (25) to (28), and (10). Branch admittance magnitude in (25) is of the same algebraic sign as its susceptance.

Novel Transformed Fast Decoupled Loadflow (NTFDL)

The NTFDL model is similar to the NFSDL model. They differ only in the defination of gain matrices.

The NTFDL(XB-version) (NTFDLXB) Loadflow

The NTFDLXB model consists of relations (23), (24), (3) to (7), (29) to (32), and (10).

$$Y1pq = \begin{cases} -Bpq & \text{for branches connected between two PV-nodes or a PV-node and the slack-node} \\ -1 / \tilde{X}_{pq} & \text{for all other branches} \end{cases} \quad (29)$$

$$Y2pq = \begin{cases} Gpq & \text{for branches connected to a PQ-node and a PV-node} \\ \tilde{B}_{pq} & \text{for branches connecting two PQ-nodes} \\ -B_{pq} & \text{for branches connecting two PV-nodes} \end{cases} \quad (30)$$

$$Y1_{pp} = \sum_{q \to p} -Y1_{pq} \quad (31)$$

$$Y2_{pp} = \begin{cases} 2b'_p + \tilde{B}_{pp} & \text{for PQ-nodes} \\ -B_{pp} & \text{for PV-nodes} \end{cases} \quad (32)$$

Where $\tilde{X}_{pq}$ is the transformed branch reactance defined in appendix by eqation (41) and $\tilde{B}_{pq}$ is the corresponding transformed element of the susceptance matrix.

The NTFDL(BX-version) (NTFDLBX) Loadflow

The NTFDLBX model consists of relations (23), (24), (3) to (7), (33) to (36), and (10).

$$Y1pq = \begin{cases} -Bpq & \text{for branches connected between two PV-nodes or a PV-node and the slack-node} \\ -\tilde{B}_{pq} & \text{for all other branches} \end{cases} \quad (33)$$

$$Y2_{pq} = \begin{cases} G_{pq} & \text{for branches connected to a PQ-node and a PV-node} \\ 1/\tilde{X}_{pq} & \text{for branches connecting two PQ-nodes} \\ -B_{pq} & \text{for branches connecting two PV-nodes} \end{cases} \quad (34)$$

$$Y1_{pp} = \sum_{q \to p} -Y1_{pq} \quad (35)$$

$$Y2_{pp} = \begin{cases} 2b'_p + \sum_{q \to p} -1/\tilde{X}_{pq} \quad \text{or} \quad = 2b'_p + 1/\tilde{X}_{pp} & \text{for PQ-nodes} \\ -B_{pp} & \text{for PV-nodes} \end{cases} \quad (36)$$

In the NFSDL NTFDLXB and NTFDLBX methods [Y1] and [Y2] are real, sparse, symmetrical and built only from network elements. Since they are constant, they need to be factorized once only at the start of the solution. Equations (23) and (24) are to be solved repeatedly by forward and backward substitutions.

[Y1] and [Y2] are of the same dimensions (m+k)*(m+k) when only a row/column of the slack-node is excluded and both are triangularized using the same ordering regardless of the node-types. It should be noted that the same indexing and addressing information can be used for the storage of both the matrices as they are of the same dimensions and sparsity structure. Unlike [Y"], It is to be noted that all the PV-nodes are also active in [Y2]. Therefore, the novel methods would pose a difficult problem of node-type switching.

ϕ_p is restricted to the maximum of -36 degrees from nonlinearity considerations for FSDL, TFDLXB, TFDLBX, NFSDL, NTFDLXB and NTFDLBX methods. However it can be tuned for the best possible convergence for any given system and it can also be vertually unrstricted -90 degrees.

Iteration Scheme

The basic iterative scheme for solving the proposed models is to solve for [$\Delta\theta$] to update [θ] and then solve (2) or (24). This is the block Gauss-Seidel approach. The scheme is block-successive which imparts increased stability to the solution process. This in turn improves convergence and increases reliability. Cycling behaviour in the iterative process of the standard iteration scheme of [1] can be avoided by simply using different convergence tolerances for the real and reactive power mismatches as suggested in [9]. The cycling behaviour and its remedy as above were originally observed by this inventor as back as in 1985 in an unaccepted paper submitted to IEEE and prepared from research conducted at the university of Roorkee. However, algorithms are given for strictly successive iteration scheme of [8].

APPENDIX

Transformation of Branch Admittance

The branch admittance transforamation for symmetrical gain matrices of the TFDLXB, TFDLBX, NTFDLXB and NTFDLBX methods is given by the following steps :

1. Compute : $\phi_{pp} = \arctan(G_{pp}/B_{pp})$ and

$$\phi_{qq} = \arctan(G_{qq}/B_{qq}) \qquad (37)$$

2. Compute the average of rotations at the terminal nodes (p and q) of a branch :

$$\phi_{av} = (\phi_{pp} + \phi_{qq}) / 2 \qquad (38)$$

3. Compare ϕ_{av} with the Limiting Rotation Angle (LRA) and let ϕ_{av} to be the smaller of the two :

$$\phi_{av} = \text{minimum}\ (\phi_{av}\ ,\ \text{LRA}) \qquad (39)$$

4. Compute transformed pq-th element of the admittance matrix :

$$G_{pq} + jB_{pq} = (\text{Cos}\phi_{av} + j\text{Sin}\phi_{av})\ (G_{pq} + jB_{pq}) \qquad (40)$$

5. Note that the transformed branch reactance is :

$$X_{pq} = B_{pq}\ /\ (G_{pq}^{2} + B_{pq}^{2}) \qquad (41)$$

and similarly

$$X_{pp} = B_{pp}\ /\ (G_{pp}^{2} + B_{pp}^{2}) \qquad (42)$$

ALGORITHM-1 (The prior art)

Super Decoupled Loadflow Algorithms (solution Steps)
Strictly Successive (1θ, 1V) Iterative Scheme :

(a) Read system data and assign an initial approximate solution. If better solution estimate is not available, set specified voltage magnitudes at PV-nodes and 1.0 p.u. voltage magnitudes at PQ-nodes. Set all the node angles equal to that of the Slack-node angle. This is referred to as the flat-start [1].

(b) Initialize iteration counts ITRP=ITRQ=r=0

(c) Form nodal admittance matrix

(d) Form (m+k) by (m+k) size matrices [Y'] and [Y"] of (1) and (2) respectively each in a compact storage exploiting sparsity.

(i) In case of SDLXB-method, the matrices are formed usig relations (8), (9) and (10).

(ii) In case of SDLBX-method, the matrices are formed using relations (11), (9) and (10).

(e) In [Y"] matrix,replace diagonal elements corresponding to PV -nodes by very large value (say 10.0**10).In case [Y"] is of dimension (m by m),this is not reqired to be performed. Factorize [Y'] and [Y"] using the same ordering regardless of the node-types. In case [Y"] is of dimension (m by m), it is factorized using different ordering than that of [Y'].

(f) Compute residues ΔP^r (PQ- and PV-nodes) and ΔQ^r (at PQ-nodes only). If all are less than the tolerance (ϵ), proceed to step (n). Otherwise follow the next step.

(g) Compute the vector of modified residues [RP] using (3) for PQ-nodes and using (5) for PV-nodes.

(h) Solve (1) for voltage angle corrections and update voltage angles using eqn. (43).

(i) Increament the iteration count ITRP=ITRP+1 and r=(ITRP+ITRQ)/2.

(j) Compute residues ΔP^r (PQ- and PV-nodes) and ΔQ^r (at PQ-nodes only). If all are less than the tolerance (ϵ), proceed to step (n). Otherwise follow the next step.

(k) Compute the vector of modified residues [RQ] using (4) for PQ-nodes only.

(l) Solve (2) for voltage magnitude corrections and update voltage magnitudes of PQ-nodes only using eqn.(44).

(m) Increament the iteration count ITRQ=ITRQ+1 and r=(ITRP+ITRQ)/2. Proceed to step (f)

(n) Calculate line flows and output the desired results.

The SDLXB and SDLBX algorithms differ only in step-d defining gain matrices in the above solution steps. Fig.1 is the flowchart of algorithm-1.

ALGORITHM-2 (containing invented steps)

Fast Super Decoupled Loadflow Algorithms (solution Steps)
Strictly Successive (1Θ, 1V) Iterative Scheme |

(a) Read system data and assign an initial approximate solution. If better solution estimate is not available, set all the nodes voltage magnitudes and angles equal to those of the Slack-node. This is referred to as the slack-start.

(b) Initialize iteration counts ITRP=ITRQ=r=0

(c) Form nodal admittance matrix

(d) Form (m+k) by (m+k) size matrices [Y'] and [Y"] of (1) and (2) respectively each in a compact storage exploiting sparsity.

(i) In case of FSDL-method, the matrices are formed using relations (13), (14), (9) and (10).

(ii) In case of TFDLXB-method, the matrices are formed usig relations (17), (18), (9) and (10).

(iii) In case of TFDLBX-method, the matrices are formed using relations (20), (21), (9) and (10).

(e) In [Y"] matrix,replace diagonal elements corresponding to PV -nodes by very large value (say 10.0**10).In case [Y"] is of dimension (m by m), this is not reqired to be done. Factorize [Y'] and [Y"] using the same ordering regardless of the node-types. In case [Y"] is of dimension (m by m), it is factorized using different ordering than that of [Y'].

(f) Compute residues ΔP^r (PQ- and PV-nodes) and ΔQ^r (at PQ-nodes only). If all are less than the tolerance (ε), proceed to step (n). Otherwise follow the next step.

(g) Compute the vector of modified residues [RP] using (3) for PQ-nodes and using (12) and (15) for PV-nodes. In (3) ϕ_p is restricted to the maximum of -36 degrees (or any other angle) from nonlinearity considerations. It can be even unrestricted for any given system (-90 degree).

(h) Solve (1) for voltage angle corrections and update voltage angles using relation (43).

$$\theta_p^r = \theta_p^{(r-1)} + \Delta\theta_p^r \qquad (43)$$

(i) Set the voltage magnitudes of PV-nodes equal to the specified values. This is required to be done only in the first iteration when slack-start is used. Increament the iteration count ITRP=ITRP+1 and r=(ITRP+ITRQ)/2.

(j) Compute residues ΔP^r (PQ- and PV-nodes) and ΔQ^r (at PQ-nodes only). If all are less than the tolerance (ε), proceed to step (n). Otherwise follow the next step.

(k) Compute the vector of modified residues [RQ] using (4). In (4) ϕ_p is restricted to the maximum of -36 degrees (or any other angle) from nonlinearity considerations. It can be even unrestricted for any given system (-90 degree).

(l) Solve (2) for voltage magnitude corrections and update voltage magnitudes of PQ-nodes only as given by relation (44). While solving (2), skip all the rows and columns corresponding to PV-nodes to increase the efficiency.

$$V_p^r = V_p^{(r-1)} + \Delta V_p^r \tag{44}$$

(m) Increament the iteration count ITRQ=ITRQ+1 and r=(ITRP+ITRQ)/2. Proceed to step (f)

(n) Calculate line flows and output the desired results.

All the above steps can also be the parts of the classical (1θ, 1V) iteration scheme of reference [1]. This algorithm is for solving loadflow problem formulated in polar coordinates. The solution of the loadflow model formulated in rectangular coordinates also involve similar steps with minor modifications. Gain matrices of the invented methods are the same for both polar- and rectangular-coordinate formulations of the loadflow problem. Fig.2 is the flowchart of algorithm-2. The FSDL-method, TFDLXB-method and TFDLBX-method differ only in step-d defining gain matrices in the above algorithm-2.

ALGORITHM-3 (invclude invented steps)

Novel Fast Super Decoupled Loadflow Algorithms (solution Steps)
Strictly Successive (1θ, 1V) Iterative Scheme |

(a) Assign an initial approximate solution. If better solution estimate is not available, set all the nodes voltage magnitudes and angles equal to those of the Slack-node. This is referred to as the slack-start.

(e) Initialize iteration counts ITRP=ITRQ=r=0

(c) Form nodal admittance matrix

(d) Form (m+k) by (m+k) size matrices [Y1] and [Y2] of (23) and (24) respectively each in a compact storage exploiting sparsity.

(iv) In case of NFSDL-method, the matrices are formed using relations (25) to (28), and (10).

(v) In case of NTFDLXB-method, the matrices are formed using relations (29) to (32) and (10).

(vi) In case of NTFDLBX-method, the matrices are formed using relations (33) to (36) and (10).

(e) Factorize [Y1] and [Y2] using the same ordering regardless of the node-types.

(f) Compute residues ΔP^r (PQ- and PV-nodes) and ΔQ^r (at PQ-nodes only). If all are less than the tolerance (ε), proceed to step (n). Otherwise follow the next step.

(g) Compute the vector of modified residues [RP] using (3) for PQ-nodes and using (5) for PV-nodes. In (3) ϕ_p is restricted to the maximum of -36 degrees (or any other angle) from nonlinearity considerations. It can be even unrestricted for any given system (-90 degrees).

(h) Solve (23) for voltage angle corrections and update voltage angles using relation (43).

(i) Set the voltage magnitudes of PV-nodes equal to the specified values. This is required to be done only in the first iteration when slack-start is used. Increament the iteration count ITRP=ITRP+1 and r=(ITRP+ITRQ)/2.

(j) Compute residues ΔP^r (PQ- and PV-nodes) and ΔQ^r (at PQ-nodes only). If all are less than the tolerance (ϵ), proceed to step (n). Otherwise follow the next step.

(k) Compute the vector of modified residues [RQ] using (4) for PQ-nodes. Compute [RP] for PV-nodes using (5). In (4) ϕ_p is restricted to the maximum value of -36 degrees (or any other angle) from nonlinearity considerations. It can be even unrestricted for any given system (-90 degrees).

(l) Solve (24) for voltage magnitude corrections at PQ-nodes and voltage angle corrections at PV-nodes. Update voltage magnitudes of PQ-nodes using relation (44) and angles of PV-nodes using relation (43). In the back substitution part of the solution of (24), skip all the PV-nodes in the calculation of voltage-magnitude corrections of PQ-nodes.

(m) Increament the iteration count ITRQ=ITRQ+1 and r=(ITRP+ITRQ)/2. Proceed to step (f)

(n) Calculate line flows and output the desired results.

All the above steps can also be the parts of the classical (1θ, 1V) iteration scheme of reference [1]. This algorithm is for solving loadflow problem formulated in polar coordinates. The solution of the loadflow model formulated in rectangular coordinates also involve similar steps with minor modifications. Gain matrices of the invented methods are the same for both polar- and rectangular-coordinate formulations of the loadflow problem. The NFSDL-method, NTFDLXB-method and NTFDLBX-method differ only in step-d defining gain matrices in the above algorithm-3. Fig.3 is the flow-chart of algorithm-3.

ALGORITHMS using GLOBAL CORRECTIONS

The algorithms-1, -2 and -3 of above involve increamental(or local) corrections. All the above algorithms can be organised to produce corrections to the initial estimate solution. It involves storage of the vectors of modified residues and replacing the relations (3),(4),(5),(12),(43) and (44) respectivly by (45),(46),(47), (48),(49) and (50). Superscript '0' in relations (49) and (50) indicates the initial solution estimate.

$$RP_p^r = (\Delta P_p^r \text{Cos}\phi_p + \Delta Q_p^r \text{Sin}\phi_p)/V_p^r + RP_p^{(r-1)} \qquad (45)$$

$$RQ_p^r = (-\Delta P_p^r \text{Sin}\phi_p + \Delta Q_p^r \text{Cos}\phi_p)/V_p^r + RQ_p^{(r-1)} \qquad (46)$$

$$RP_p^r = \Delta P_p^r / V_p^r + RP_p^{(r-1)} \qquad (47)$$

$$RP_p^r = \Delta P_p^r / (K_p * V_p^r) + RP_p^{(r-1)} \qquad (48)$$

$$\theta_p^r = \theta_p^0 + \Delta\theta_p^r \qquad (49)$$

$$V_p^r = V_p^0 + \Delta V_p^r \qquad (50)$$

RECTANGULAR COORDINATE FORMULATIONS OF THE INVENTED LOADFLOW METHODS

This involves following changes in the equations describing the loadflow models formulated in polar coordinates.

(i) Replace θ and $\Delta\theta$ respectively by f and Δf in equations (1), (23), (24), (43) and (49).

(ii) Replace V and ΔV respectively by e and Δe in equations (2), (24), (44) and (50).

(iii) Replace V_p by e_p or e_s in equations (3), (4), (5), (12), (45), (46), (47) and (48). The subscript 's' indicates the Slack-node variable.

(iv) After calculation of corrections to the imeginary part of complex voltage (Δf) of PV-nodes and updating the imaginary component (f) of PV-nodes, calculate real component by :

$$e_p = V^2_{p(specified)} - f^2_p \qquad (51)$$

COMPACT STORAGE SCHEMES FOR GAIN MATRICES OF THE FSDL METHOD

Two compact matrix storage schemes for gain matrices of the FSDL method are described in the following.

(1) When network shunts are ignored (FK=0.0), [Y"] becomes the submatrix of [Y']. In this scheme, [Y'] is factorized using optimal ordering regardless of node-types along with the following procedure :

1. Identify PQ-nodes in the composite path of all PV-nodes.

2. Reload and refactor all row/columns of these PQ-nodes using partial refactorization method PR1 of [13]. Store these factors separately.

3. When solving for ΔV using factors of [Y'] :
   (i) all PV-nodes and factor elements with indices corresponding to PV-nodes are skipped. Zeroing of reactive power mismatches at PV-nodes is not required.
   (ii) for PQ-nodes of the path, separately stored factors as in step-2 above are used along with the other factors of [Y'] in forward-backward operations.

The above procedure is implemented. For 118-node system, there are only 18 PQ-nodes in the composite path of all 53 PV-nodes. Each of the gain matrices [Y'] and [Y"] is having 117-row/columns for 118-node system, and the total of 234-row/columns are to be factorized and stored for conventional 2-matrix solution. Threfore the proposed second scheme can be said to be saving 42% (99/234=0.42) of the factorization effort and core memory. This saving rises to the maximum 50% for systems without PV-nodes.

(2) When network shunts are ignored (FK=0.0), [Y"] becomes the submatrix of [Y']. In the single matrix version of the FSDL method only [Y'] is factorized and stored. This is achieved exactly by placing PV-nodes after all PQ-nodes and by allowing optimal ordering only within each group. While solving (2) for ΔV, all PV-nodes and factor elements with indices corresponding to PV-nodes are skipped. Zeroing of reactive power mismatch at PV-nodes is not required. Apperantly, 50% reduction in the matrix storage is achieved in the absence of PV-nodes.

PV-node Q-limit Adjustment for the FSDL method

When the power flow solution is moderately converged, any Q-limit violations should be corrected. Any violated PV-node is converted to the PQ-type with the rective generation set at the limiting value. The voltage of the converted node is subsequently compared to the scheduled value and the node is reconverted to the PV-type, if any of the back-off conditions are satisfied.

The conventional node-type switching approach is more suitable for the handling of the PV-node Q-limiting. The switching of node-types involves the insertion/delation of eqalities into/from (2). This can be achieved efficiently by partial matrix refactorization and factor updating methods. Partial Refactorization Method-1 (PR1)[13] can be used to update [Y"] in order to account for changes in the node status (regulated or nonregulated). The efficiency of PR1 is inversely proportional to the number of node status changes. Two efficient techniques of the node-type switching are described in the following.

(1) When network shunts are ignored (FK=0.0) or accounted by alternative ways, a reactivated row/column by the removal of the large diagonal corresponding to a PV-node in [Y"] is identical to that in [Y']. It is this feature of the FSDL method exploited to enhance the efficiency of the node type switching using the following procedure. This is convenient with the simple variant of the FSDL method mentioned before.

1. find the composite path of PV-nodes switched to PQ-type

2. find the composite path of the rest of the PV-nodes

3. refactor only rows/columns of [Y"] that constitute common path of steps 1 and 2. The factored rows/columns of [Y'] in the uncommon path of step 1 can be used for the partial refactorization of [Y"]

4. while solving (2), use factors from [Y'] in the uncommon part of the path of step 1 along with other factos of [Y"].

When all the PV-nodes of the system are switched to PQ-type, [Y'] is used for solving (2) and no partial refactorization in [Y"] is required. Also when common path to be determined in step-3 does not exist, partial refactorization is not required.

(2) The compact storage scheme (1) for the FSDL method described above inherently provides for efficient implimentation of node-type switching used for PV-node Q-limit adjustment. The procedure constitutes the following steps.

1. PQ-nodes in the composite path of all PV-nodes are known and their rows/columns are factored and stored separately from those of [Y'] for unadjusted solution.

2. Identify PQ-nodes in the composite path of current PV-nodes.

3. Identify PQ-nodes which are not common in steps 1 and 2.

4. Carry out Reverse Correction Partial Matrix Refactorization along the composite path of PQ-nodes of step-3 on separately stored factors of step-1. Use large diagonals in rows/columns of PQ-nodes of step-3.

If no PQ-node is identified in step-3, Reverse correction Partial matrix refactorization of step-4 is not required to be performed.

REFERENCES

1. B.Stott and O.Alsac, "Fast Decoupled Loadflow", IEEE Trans., Vol.PAS-93, PP.859-869, May/June 1974.

2. F.F.Wu, "Theoretical Study of the Convergence of the Fast Decoupled Loadflow",IEEE Trans., Vol.PAS-96, PP.268-275, Jan./Feb. 1977.

3. S.Deckman, A.Pizzolante, A.Monticelli, B.Stott and O.Alsac, "Numerical Testing of Power System Loadflow Equivalents", IEEE Trans., Vol.PAS-99, No.6, pp.2292-2300, Nov./Dec. 1980.

4. D.Rajicic and A.Bose, "A modification to the Fast Decoupled Loadflow for networks with high R/X ratios",IEEE Trans., Vol.PWRS-3, No.2, pp.743-746, May 1988.

5. N.R.Rao and G.M.Krishna, "A new decoupled model for state estimation of power systems", IFAC Symposium on Theory and Application of Digital Control, Vol.2, 5-7 Jan.1982, New-Delhi, India.

6. W.Hubbi and A.Refsum, "Starting algorithm and modification for Newton-Raphson loadflow method", Electr. Power and Energy Systems, Vol.5, No.3, pp.166-172, July 1983.

7. P.H.Haley and M.Ayres, "Super decoupled loadflow with distributed slack bus", IEEE Trans., Vol.PAS-104, pp.104-113, January 1985.

8. Robert A.M. Van Amerongen, "A general-purpose version of the Fast Decoupled Loadflow",IEEE Trans., Vol.PWRS-4, pp.760-770, May,1989.

9. A.Monticelli, A.Garcia and O.R.Saavedra, "Fast Decoupled Loadflow : Hypothesis, derivations and testing", Presented at IEEE/PES Winter Meeting, New York, January 29-Feb.3,1989. (Paper No. 89 WM 172-8 PWRS)

10. P.E.Crouch, D.J. Tylavsky, H.Chen, L.Jarriel and R.Adapa, "Critically coupled Algorithms for solving the Power Flow Equation", IEEE Trans.,, Vol.PWRS-7, pp.451-457, February,1992.

11. M.H.Haque, "Novel decoupled loadflow method",IEE Proceedings Part-C,Vol.140, No.3, May 1993.

12. S.B.Patel, "Fast Super Decoupled Loadflow",IEE Proceedings Part-C,Vol.139, No.1, January 1992.

13. S.B.Patel, "Transformation based Fast Decoupled Loadflow", Proceedings of 1991 - IEEE region 10 international conference (IEEE TENCON'91, New Delhi), Vol.I, pp.183-187, August 1991.

2107388

14. S.M.Chan and V.Brandwajan, "Partial Matrix Refactorization", IEEE Trans., Vol.PWRS-1, pp.193-201, Feb.1986.

I CLAIM :

(a) To have invented three Super Decoupled Loadflow methods (FSDL, TFDLXB and TFDLBX) both in Polar coordinate and Rectangular coordinates formulations, their Novel versions (NFSDL, NTFDLXB and NTFDLBX), and their all possible hybrid cobinations. Also I claim to have invented the technique of producing Global corrections as given by relations (45) to (50).

(b) Specifically the invention involves the use of the following seven(7) items in the methods of (a):

(i) the definitions of the gain matrices of the six-methods of (a) corresponding to steps-d in algorithm-2 and algorithm-3, for both polar and rectangular formulations of the loadflow problem. Though explicit definitions of unsymmetrical gain matrices of Pθ-subproblem are not given, they are obvious for all the six methods and they are also claimed by this inventor as simple modifications.

(ii) restriction of rotation angle ϕ_p to the maximum of -36 degrees (any other angle) in relations (3),(4),(45) and (46) from nonlinearity considerations, for both polar and rectangular coordinate formulations of the loadflow problem.

(iii) modification of real power mismatch at PV-nodes according to relations (12) and (15) in FSDL, TFDLXB and TFDLBX-

methods formulated in both polar and rctangulr coordinates. This in general is the technique to modify the known vector to ensure the coefficient/gain matrix symmetrical. It can be used in all possible computer algorithms (including all other approaches of the formulation of the loadflow problem) and real-time/on-line/off-line applications.

(iv) computation of angle corrections and updating for PV-nodes along with the Voltage magnitude corrections while solving equation (24) for NFSDL, NTFDLXB and NTFDLBX methods. In the back-substitution part of the solution of (24), I claim to have invented the technique to skip all the rows and columns corresponding to PV-nodes for calculation of voltage magnitude corrections of PQ-nodes. This also applies when the novel methods are formulated in rectangular coordinates.

(v) the Slack-start procedure for all the decoupled loadflow methods and in particular for the six methods of (a) above.

(vi) similar decoupled methods as of (a) can also be used for solving simultaneous equations appearing in other areas of analysis, operation and control.

(vii) The six invented methods of unadjusted loadflow solution can be used for adjusted solution by adding some more steps in the algorithms, state estimation, contingency analysis and in variety of advanced power network analysis and control.

(c) Also I claim to have invented two compact storage schemes for gain matrices of the FSDL method and two efficient procedures of the node-type switching implementations for the FSDL method as described in the above.

Dated this 7 th day of november 1993.

S.B.Patel

Signature of the Inventor S.B.Patel

2107388.

Name : S. B. PATEL
No. :

No. of Sheets : 3
Sheet No. : 1

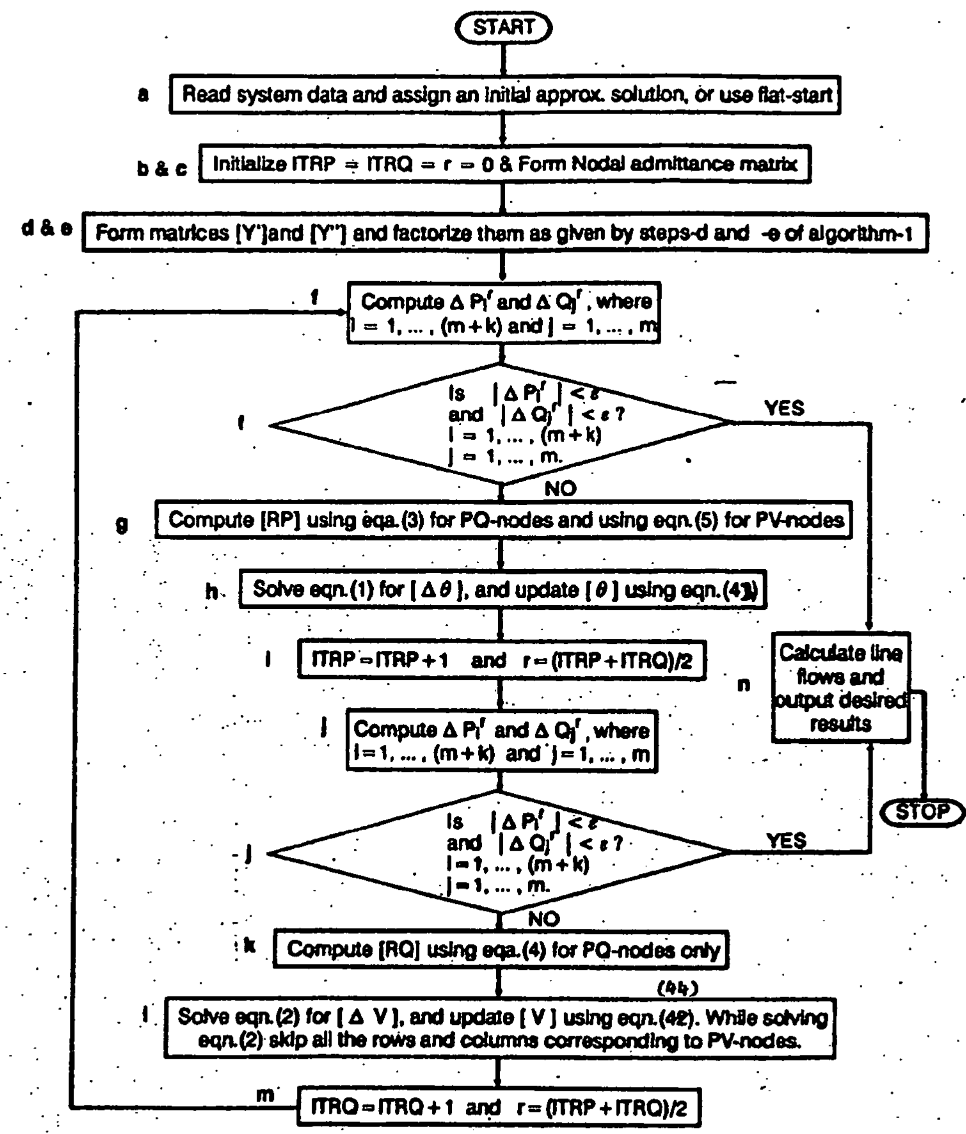

Fig. 1 Flow-chart of unadjusted load flow solution algorithm-1.
It is the same for SDLXB and SDLBX methods. (flow-chart of the prior art)

(S. B. PATEL)
Applicant

Name : S. B. PATEL
No. :

No. of Sheets : 3
Sheet No. : 2

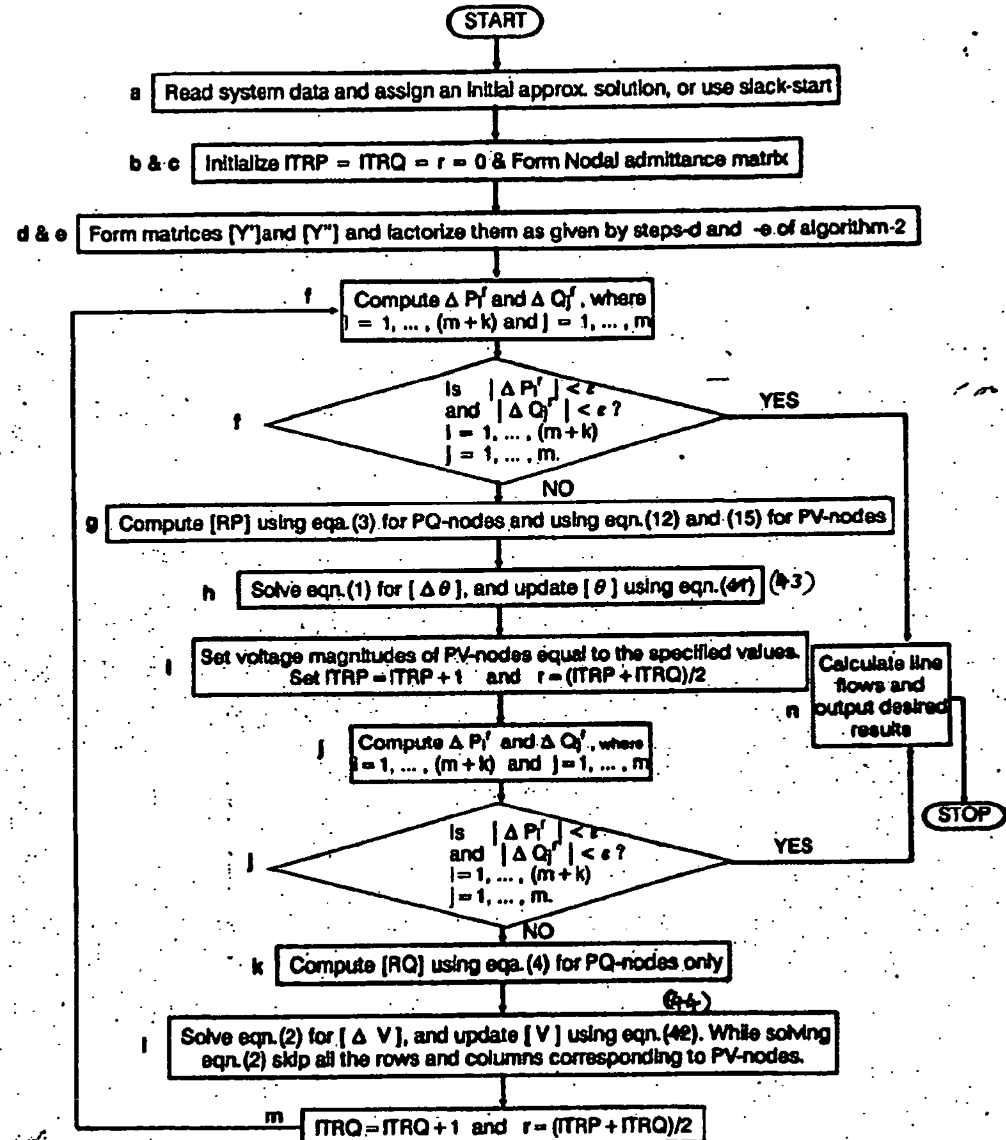

Fig. 2 Flow-chart of unadjusted load flow solution algorithm-2.
It is the same for FSDL, TFDLXB and TFDLBX methods. (flow-chart of invited methods)

(S. B. PATEL)
Applicant

Name : S. B. PATEL
No. :

No. of Sheets : 3
Sheet No. : 3

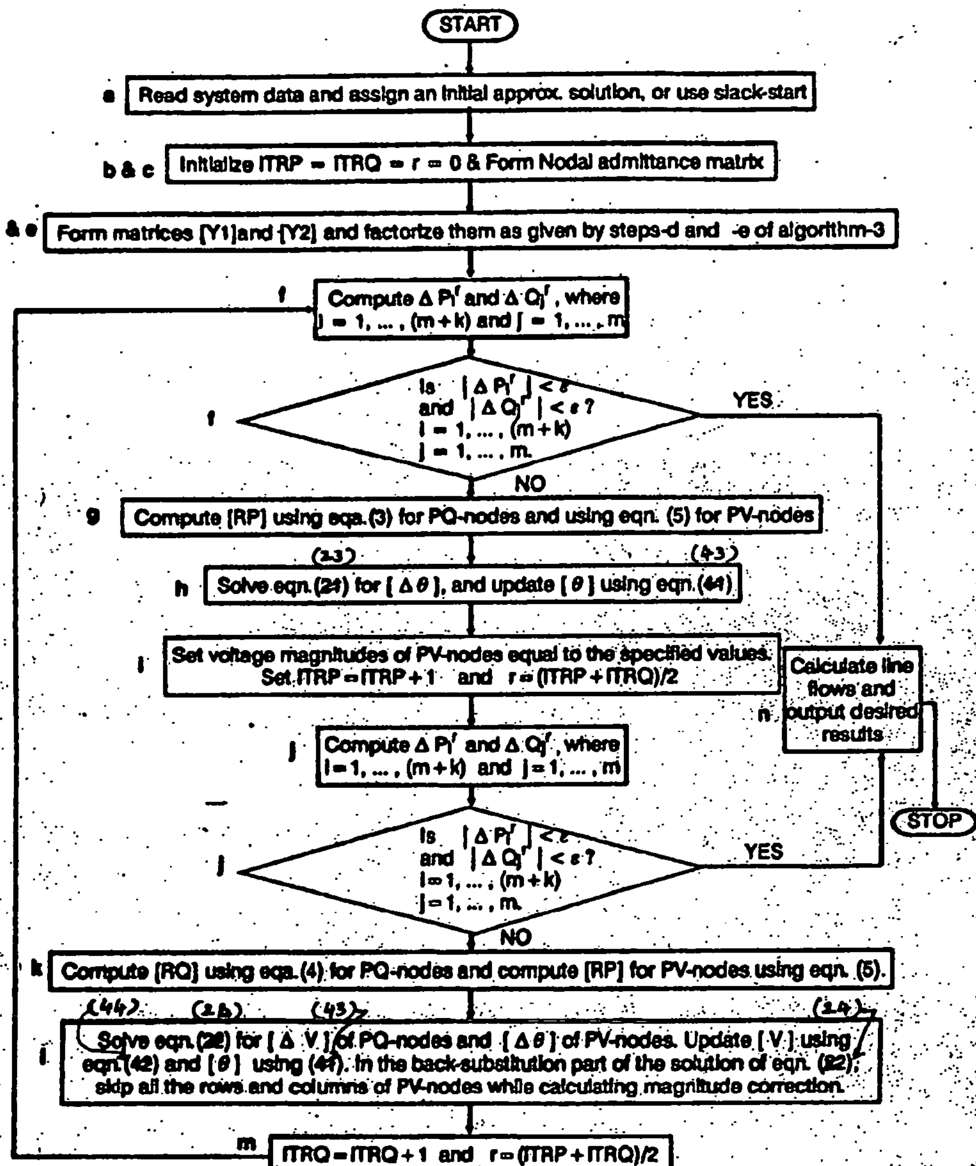

Fig. 3 Flow-chart of unadjusted load flow solution algorithm-3. It is the same for NFSDL, NTFDLXB and NTFDLBX methods. (flow-chart of invented methods)

(S. B. PATEL)
Applicant

DERWENT-ACC-NO: 1995-240975
DERWENT-WEEK: 199532

TITLE: Super decoupled method for steady state loadflow analysis of power system using computer algorithms to process raw data

INVENTOR: PATEL S B

PATENT-ASSIGNEE: PATEL S B[PATEI]

PRIORITY-DATA: 1993CA-2107388 (November 9, 1993)

PATENT-FAMILY:

PUB-NO	PUB-DATE	LANGUAGE
CA 2107388 A	May 10, 1995	EN

APPLICATION-DATA:

PUB-NO	APPL-DESCRIPTOR	APPL-NO	APPL-DATE
CA 2107388A	N/A	1993CA-2107388	November 9, 1993

INT-CL-CURRENT:

TYPE	IPC DATE
CIPS	H04N5/30 20060101

ABSTRACTED-PUB-NO: CA 2107388 A

BASIC-ABSTRACT:

The super decoupled loadflow methods include FSDL, TFDLXB and TFDLBX, both in polar and cartesian co-ordinate forms, their novel versions and all possible hybrid combinations. The gain matrices of the six methods are defined. The rotation angle (?p) is restricted to -36?.

A real power mismatch at PV-nodes is modulated to ensure that the coefficient/gain matrix is symmetrical. It can be used in all possible computer algorithms. Angle corrections are computed and updated for PV-nodes along with voltage magnitude corrections while solving certain equations within the algorithms. The rows and columns corresp. to PV-nodes may be skipped for calculation of voltage magnitude corrections of PQ-nodes.

USE/ADVANTAGE - Steady state analysis of electrical power network. Reliable operation. Simplified algorithms involve fewer calculations per iterations.

CHOSEN-DRAWING: Dwg.2/3

TITLE-TERMS: SUPER DECOUPLE METHOD STEADY STATE ANALYSE POWER SYSTEM COMPUTER ALGORITHM PROCESS RAW DATA

DERWENT-CLASS: T01 X12

EPI-CODES: T01-J08; T01-S; X12-H05;

SECONDARY-ACC-NO:

Non-CPI Secondary Accession Numbers: 1995-187940